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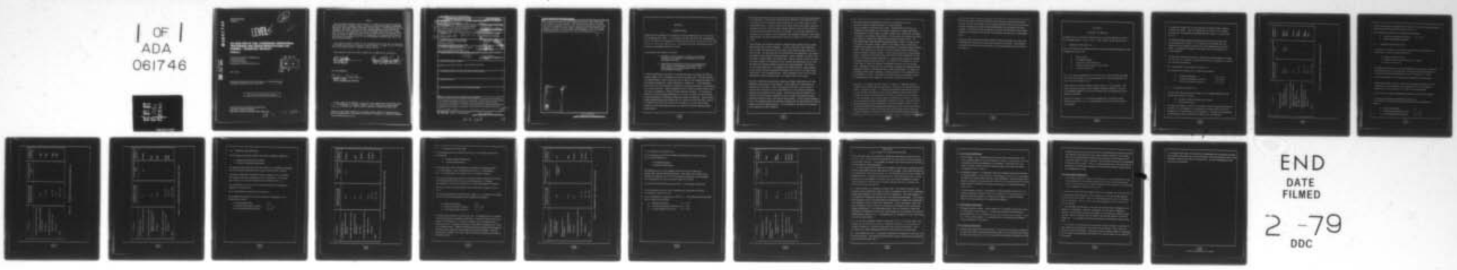

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AFFDL-TR-78-96
Volume I

LEVEL II

AN ANALYSIS OF FUEL CONSERVING OPERATIONAL PROCEDURES AND DESIGN MODIFICATIONS FOR BOMBER / TRANSPORT AIRCRAFT
Volume I

DYNAMICS RESEARCH CORPORATION
SYSTEMS DIVISION
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JULY 1978

TECHNICAL REPORT AFFDL-TR-78-96, Volume I – Executive Summary
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AIR FORCE FLIGHT DYNAMICS LABORATORY
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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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Various proposed improvements in the design and operational procedures for bomber/transport aircraft are evaluated. The evaluation is performed in terms of the estimated savings in fuel consumption and in Direct Operating Cost (DOC). As an aid in the evaluation of design modifications, graphs of fuel and DOC savings as a function of the design parameters are developed. over

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These graphs are based on actual mission trajectory data rather than some typical trajectory profile. The actual mission data is presented in terms of histograms which provide statistical information concerning altitude, air speed, take-off weight, landing weight, and mission time. Separate analyses are performed on the following aircraft: the B-52G, the B-52H, the KC-135, the C-141, the C-130, and the C-5A.

SECTION 1

INTRODUCTION

This study was motivated by a concern for energy conservation and a concern for the escalating cost of fuel. It is estimated that over 54% of the fuel requirements of the Air Force are consumed by the following five aircraft: the B-52, the KC-135, the C-141, the C-130, and the C-5A. The scope of this fuel conservation study is confined to addressing these five aircraft.

The objective of the study is two-fold:

1. Quantify how improvements in design or operational procedures will impact fuel consumption and direct operating costs (DOC).

2. Determine the sensitivity of the fuel consumption and DOC results to uncertainties (variations) in the aircraft parameters, instrumentation errors, and environmental conditions.

A major contribution of this study is the approach taken to generate the effect of design changes on fuel consumption and direct operating cost. With this approach the design change is first broken down into its effect on the design parameters (i.e., aerodynamic parameters, engine parameters, weight, etc.). Then sensitivity plots of fuel and DOC savings as a function of each design parameter are generated for each aircraft type. These sensitivity plots are based on actual mission trajectory data, as opposed to "typical" mission trajectory profiles. To evaluate the impact of some new design modification in the fleet, the procedure thus consists of determining how the individual design parameters are effected. Then the appropriate sensitivity plots are entered, and the contributions from each plot (positive or negative) are combined to obtain the total effect on fuel and DOC savings. Within this study the sensitivity plots are employed to evaluate specific design modifications.

It is important to note that the sensitivity plots employed in the above procedure are based on how the aircraft were actually flown, not on some typical or optimum flight profile. Thus the results of the design modification impact analyses presented here are the fuel and DOC savings expected if the aircraft continue to be flown the way they have been flown in the past. This realistic approach is in contrast to prior studies in which estimated fuel savings are based on a particular flight profile, one which often cannot be flown as a result of ATC or other restrictions.

Prior studies were limited to typical or optimum flight profiles because actual flight profile data were not available. As part of this study, DRC undertook a task to locate and incorporate into the study actual mission profile data for the five aircraft. The data found has been transformed into histograms, thus providing spectra of the mission profile parameters, such as altitude, air speed, take-off weight, landing weight, and mission time. Several sources of data were used and cross-checked to determine the data's validity and applicability to the study. By means of an Interim Mission and Cost Data Analysis Report, DRC Report M-314U dated August 1977, coordination was obtained with the using commands on the mission data and operational procedures to be used for the final results of the study. The resulting data base, which represents actual Air Force fleet operation for the five aircraft types, is in itself a major contribution.

Many fuel conservation operational changes and design modifications have been identified and proposed by prior studies. These studies are summarized and referenced in this report. Thus, the purpose of this study is not so much to discover new procedures for fuel conservation as it is to evaluate procedures identified and proposed in prior studies. Various operational procedures to be evaluated include trajectory optimization while airborne and improved ground handling procedures prior to take-off and after landing. Various design modifications to be evaluated include the addition of winglets and the replacement of current engines with more efficient engines. As an alternative, the effect of a reduction in fuel allocation is also evaluated.

The optimal control methodology employed for developing the mission spectrum analysis computer program is a unique approach based on singular perturbation theory (SPT). Optimal flight trajectories are dependent on many factors such as external configuration, engine performance characteristics, system weight, air traffic control (ATC) constraints, atmospheric conditions, and mission requirements. The derivation of the optimal trajectory must reflect the differences among aircraft/missions in those factors. The SPT Methodology (called Extended Energy Management, EEM), is unique in that it provides an inherently analytic solution to the optimal control problem that satisfies all necessary and sufficiency conditions for a complete nonlinear dynamic model, while enforcing a broad class of state and control variable constraints. Since the solution is largely analytic, it can be used directly for on-board digital control. Significant contributions have been made with this methodology in being able to overcome the historic difficulties in obtaining rapid solutions to nonlinear, constrained optimal control problems. This EEM SPT Methodology was utilized in this study to obtain the trajectory optimization results for the five aircraft types. Sensitivity results are given to determine the impact of optimal operating procedures relative to existing air traffic control requirements. In addition, an appendix presents results regarding a recent controversy in the literature about the optimality of cruise. This appendix describes under what condition cruise is not optimizing and gives results for two aircraft considered in this study.

This report is organized into two volumes. Volume I is a separate executive summary of the major objectives and results. Volume II is the detailed technical report. Sections 2 through 6 of Volume II present general information about the aircraft, models, procedures and the analysis approach utilized; then Section 7 provides the specific numerical results. Section 2 gives the data sources and a general description of the mission profiles and operating cost models. Section 3 gives the analytical problem formulation, definitions of terms, and describes the mission spectrum analysis simulation tool that was developed. Section 4 gives the analysis approach for assessing operational procedures (airborne and ground) that conserve fuel. Section 5 discusses the analytical approach for addressing design modifications, and Section 6 describes the sensitivity analysis approach.

Section 7 provides numerical results for each aircraft in separate subsections. Included for each aircraft type are the mission spectrum data and the fuel and DOC savings resulting from specific design modifications and operational procedure changes. Section 8 discusses the impact of reduced fuel allocation on operational readiness, and Section 9 presents the overall study conclusions and recommendations.

Section 2 of this executive summary contains a separate summary of results and conclusions for each of the five aircraft considered in the study. Then Section 3 reproduces the overall study conclusions and recommendations found in Section 9 of Volume II.

SECTION 2

SUMMARY OF RESULTS

Summarized here in separate subsections are the results obtained for each of the following aircraft: C-141, C-5A, C-130E, B-52G, B-52H, and KC-135.

2.1 SUMMARY FOR THE C-141

Each of the following operational procedures/design modifications generated fuel savings greater than 1.5%:

- fillet revision
- retrofitting winglets
- removal of vortex generators
- flying at optimum altitude and air speed
- reduced reserve fuel

The C-141 wing-to-fuselage fillet can be revised to reduce air flow separation. The annual fuel savings will be approximately 5.8%, and the modification cost can be recovered within 4 years.

Under present operating conditions winglets offer a 2.7% fuel savings. Even higher savings are possible under optimum operating conditions. The cost of retrofitting winglets can be recovered within three years based on present operating conditions.

Annual fuel savings of 1.7% have been estimated due to removal of vortex generators from the C-141. The modification cost can be recovered within three months.

An annual fuel savings of 3.3% can be achieved by flying at higher altitudes and slower air speed. Since the ASIMIS tape data for the C-141 missions is not precise, the estimated fuel savings can be as high as 7.6% and as low as 1.6%.

The ASIMIS tape data indicates that reserve fuel carried by this aircraft is much higher than required. A 3.7% savings in fuel annually has been estimated for the reduction of reserve fuel to the maximum set of requirements. An additional 2% savings is achievable with a more moderate set of requirements.

All other fuel conserving procedures investigated produced annual fuel savings of 1.5% or less, or a specific savings factor could not be assigned as a result of input variable uncertainties.

These conclusions are summarized in Table 2.1.

The potential fuel savings can be categorized as follows:

• Design modifications	10.2 - 13.2%
• Airborne operational procedures	4.8 - 5.8%
• Ground operational procedures	6.7 - 9.2%

2.2 SUMMARY FOR THE C-5A

The two items which produced more than a 1% fuel savings annually are both operational procedures: namely,

- cruising at optimum altitude and air speed
- reduced reserve fuel

An annual fuel savings of 5.8% can be achieved by flying at optimum altitude and air speed. A fuel savings of 0.9 is possibly by reducing reserve fuel to the maximum set of requirements, and an additional 1.3% savings can be generated by establishing a more moderate set of reserve fuel requirements.

Procedures	Estimated Percentage Annual Fuel Savings	Break Even Period Years	Confidence In Estimates
Design Modification			
Fillet revision	5.8	3.4	Medium
Retrofitting winglets	2.7-5.7	1.4 -3	High
Vortex generator removal	1.7	.25	Medium
Airborne Operational Procedures			
Flying at optimum altitudes and air speed	3.3	-	Medium
Aft c.g. operations	1	-	High
All others	.5 - 1.5	-	Medium
Ground Operational Procedures			
Reduced reserve fuel	3.7 - 5.7	-	High
Engine Maintenance	1.5	-	Medium
All others	1.5 - 2	-	High
Total	21.7 - 28.2		

Table 2.1 ESTIMATED FUEL SAVINGS FOR THE C-141

These conclusions are summarized in Table 2.2. Note that no design modifications are seriously being considered for the C-5A.

The potential fuel savings can be categorized as follows:

- Airborne operational procedures 6.8 - 7.3%
- Ground operational procedures

2.3 SUMMARY FOR THE C-130E

More than a 1% savings in fuel annually is generated by the following three operational procedures/design modifications:

- fuselage afterbody strakes
- flying at optimum cruise altitude and air speed
- reduced reserve fuel

Fuselage afterbody strakes revise the fuselage air flow patterns to reduce air flow separation and the resulting drag. The annual fuel savings estimate is 5%, and the associated modification cost can be recouped in 3.5 years.

Annual fuel savings of 5.2% are possible by optimum cruise procedures.

Annual fuel savings of 1.3% are produced by reducing the reserve fuel to the maximum set of requirements, and an additional 0.8% in fuel savings is possible with a more moderate set of reserve fuel requirements.

Each of the other items investigated generated less than a 1% fuel savings.

The above conclusions are summarized in Table 2.3.
The potential fuel savings due to the various items can be categorized as follows:

- Design modifications 5%
- Airborne operational procedures 7.2 - 7.7%
- Ground operational procedures 3.3 - 5.6%

Procedures	Estimated Percentage Annual Fuel Savings	Break Even Period Years	Confidence In Estimates
Airborne Operational Procedures			
Cruising at optimum altitude and air speed	5.8	-	High
All others	1 - 1.5	-	High
Ground Operational Procedures			
Reduce reserve fuel	.9 - 2.2	-	High
All others	1 - 2	-	High
Total	8.7 - 11.5		

Table 2.2 ESTIMATED FUEL SAVINGS FOR THE C-5A

Procedures	Estimated Percentage Annual Fuel Savings	Break Even Period Years	Confidence In Estimates
Design Modifications			
Fuselage after body strakes	5	3.5	Medium
Airborne Operational Procedures			
Flying at optimum cruise altitude and airspeed	5.2	-	High
All others	2-2.5	-	High
Ground Operational Procedures			
Reduce reserve fuel	1.3 - 2.1	-	High
All others	2 - 3.5	-	High
Total	15.5 - 18.3		

Table 2.3 ESTIMATED FUEL SAVINGS FOR THE C-130E

2.4 SUMMARY FOR THE B-52G

The two items listed below produced more than 1% savings in annual fuel:

- manual surge bleed valve override
- trajectory optimization procedures

The manual surge bleed valve overrride results in a 1.5% annual fuel savings, and the associated modification cost can be recovered within 2.5 years.

Trajectory optimization encompasses flying at optimum cruise conditions and keeping the aircraft configuration clean during descent. The annual fuel savings due to trajectory optimization is estimated to be 2.1%.

The fuel savings due to each of the remaining procedures investigated is estimated to be less than 1%.

These conclusions are summarized in Table 2.4.

The potential fuel savings due to all the procedures investigated can be categorized as follows:

• Design modifications	1.5%
• Airborne operational procedures	2.1 - 3.1%
• Ground operational procedures	2.3 - 3%

Procedures	Estimated Percentage Annual Fuel Savings	Break Even Period Years	Confidence In Estimates
Design Modifications			
Manual surge bleed valve override	1.5	2.5	Medium
Airborne Operational Procedure			
Trajectory optimization procedures	2.1	-	High
All others	0 - 1	-	Medium
Ground Operaational Procedures			
Engine maintenance	1-1.5	-	Medium
All others	.8 - 1.5	-	Medium
Total	5.4 - 7.6		

Table 2.4 ESTIMATED FUEL SAVINGS FOR THE B-52G

2.5 SUMMARY FOR THE B-52H

The following two items result in more than a 1.5% savings in annual fuel consumption:

- turbofan engine modifications
- trajectory optimization

Several potential retrofit modifications are possible for reducing the SFC of turbofan engines. These modifications offer up to a 2.8% savings in fuel. The modification cost estimates are not available at present.

The trajectory optimization involves cruising at optimum altitude and air speed and descending with the aircraft in a clean configuration. An annual fuel savings of 2.9% has been estimated due to these optimization procedures.

Each of the other fuel conservation items produced fuel savings of 1.5% or less.

The above conclusions are summarized in Table 2.5. The annual fuel savings due to all the items investigated can be categorized as follows:

• Design modifications	2.8%
• Airborne operation procedures	2.9 - 3.9%
• Ground operational procedures	1.8 - 3%

24 illustrate the sensitivity of range factor, RF, to deviations from the optimum cruise mach number and altitude, respectively. These plots can be used in conjunction with Equation (6.1) to obtain the increase in fuel consumption due to instrument errors. Changes in cruise mach also affect the mission time, which in turn affect the DOC. Altitude variations also impact mission time because for a constant mach cruise the true air speed will vary with altitudes. The DOC models given in Section 7.6.3 can be used to obtain the sensitivity of the DOC to instrument errors.

Procedures	Estimated Percentage Annual Fuel Savings	Break Even Period Years	Confidence In Estimates
Design Modifications			
Turbofan engine modifications	2.8	Not known at Present	Low
Airborne Operational Procedures			
Trajectory optimization procedures	2.9	-	High
All others	0-1	-	Medium
Ground Operational Procedures			
Engine maintenance	1 - 1.5	-	Medium
All others	.8 - 1.5	-	Medium
Total	7.5 - 9.7		

Table 2.5 ESTIMATED FUEL SAVINGS FOR THE B-52H

2.6 SUMMARY FOR THE KC-135

The two operational procedures/design modifications which produced more than 1.5% fuel savings are

- retrofitting winglets
- trajectory optimization

Retrofitting the KC-135 with winglets will result in a 3.1% annual fuel savings under present operating conditions. Even higher fuel savings will be produced by winglets if the KC-135 are operated at optimum cruise conditions. The modifications cost can be recovered within 6 1/2 years.

The trajectory optimization procedures offer a 3.4% savings in annual fuel.

The fuel savings due to each of the remaining fuel conserving procedures were found to be less than 1.5%.

These conclusions are summarized in Table 2.6. The total annual fuel savings can be categorized as follows:

• Design modification	3.1 - 7.8%
• Airborne operational procedures	3.9 - 4.9%
• Ground operation procedures	3.0 - 4.2%

Procedures	Estimated Percentage Annual Fuel Savings	Break Even Period Years	Confidence In Estimates
Design Modifications			
Retrofitting winglets	3.1 - 7.8	2.5 - 6.4	High
Airborne Operational Procedures			
Trajectory optimization	3.4	-	High
All others	.5 - 1.5	-	Medium
Ground Operational Procedures		-	
Engine maintenance	1- 1.5	-	Medium
Reduce reserve fuel	1 - 1.5	-	Medium
All others	.5 - 1.2	-	Medium
Total	9.5 - 16.9		

Table 2.6 ESTIMATED FUEL SAVINGS FOR THE KC-135

SECTION 3

CONCLUSIONS AND RECOMMENDATIONS

This study addressed improvements in design and operational procedures for the C-141, C-5A, C-130E, B-52G, B-52H and KC-135 aircraft with fuel conservation as the major objective. The findings and results of this study lead to the following conclusions and recommendations.

1. Of all the operational procedures investigated, flying close to optimum altitude and air speed offers the best opportunity for fuel savings. Since these savings can be realized with little effort and cost, it is recommended that this item be given the highest priority. It should be noted that the Air Force and industry are currently involved in the development of on-board real time energy management systems whose function is to aid the pilot in flying at optimal altitudes, air speeds, and climb and descent trajectories.

2. Next in priority is a reduction in reserve fuel. The amount of reserve fuel carried by the aircraft under study (no data is available for the B-52's) is generally higher than required by the current Air Force regulations. Thus fuel savings can be achieved by reducing the reserve fuel to the current requirements. Also during the sensitivity study it was determined that additional fuel savings can be generated by relaxing the current reserve fuel regulations. These regulations, which have been in effect for years, should be re-evaluated with respect to the current operational environments. It is recommended that a study be conducted to assess the feasibility of relaxing the reserve fuel requirements and to determine the technical advancements required (e.g., in navigation and ATC equipment) to allow this relaxation in the requirements.

3. For the cargo transport aircraft in this study (C-141, C-5A and C-130E), fuel savings can be achieved by the aft c.g. operation since the c.g. location can be readily influenced by a proper distribution of the fuel load and payload. Thus a revision of the cargo loading procedures for these aircraft is recommended.

4. The potential fuel conserving design modifications investigated in this study vary with aircraft type. The following discusses these design improvements individually for each aircraft under study:

C-141 Design Modifications

- Fillet revision - It is estimated that the revised wing-to-fuselage fillet will save 35 million gallons of fuel (5.8%) annually. However, if the entire C-141 fleet is stretched, then this modification is not required. If the fleet is not converted, the fillet revision should be considered since the break-even period is estimated to be 3.4 years.

- Retrofitting winglets - A preliminary analysis of winglets indicates that almost 16 million gallons (2.7%) of fuel can be saved annually for the C-141 with a potential for higher fuel savings under optimum cruise conditions. Since the break-even period is estimated to be less than three years, it is recommended that a detailed design analysis be performed to assess the feasibility of retrofitting winglets on the C-141.

- Vortex generator removal - Elimination of vortex generators from the C-141 wing are estimated to produce annual fuel savings of 10.5 million gallons (1.7%). Since the break-even period is less than three months, the efforts directed toward the vortex generator are certainly cost-effective.

C-130E Design Modifications

- Fuselage afterbody strakes - These additions to the fuselage would reduce drag by revising the air flow patterns. An annual fuel savings of approximately 6 million gallons is (5%) is estimated and the break-even period is less than 3.5 years As a result of these figures, it is concluded that a more detailed investigation of this modification is warranted.

B-52G Design Modifications

- Manual engine surge bleed valve override - The B-52G aircraft has an automatic air bleed valve which remains open when the engine is in the possible stall region. An annual fuel savings of 1.5% can be achieved by operating four engines at power

settings where the surge bleed values will be automatically closed and the other four engines at high power with the values manually operated by the co-pilot. The cost of the modification to allow manual operation of these values can be recovered within 2.5 years. However, the procedure will result in an increased work load for the co-pilot. Thus, it is recommended that a work load study be conducted to determine the feasibility of this procedure before a final decision for modification is made.

KC-135 Design Modifications

- Retrofitting winglets-An annual fuel savings of 14.2 million gallons(3.1%) has been estimated for retrofitting winglets on the KC-135, and the break-even period is estimated to be 6.4 years. Based on these results, it is recommended that winglets be installed on the KC-135.

5. The use of JP-8 grade fuel instead of the JP-4 currently used by the Air Force would generate approximately 57 million gallons (3.3%) of fuel savings annually for the aircraft under study. Thus it is recommended that the use of JP-8 grade fuel be considered. The Air Force is already shifting from JP-4 to JP-8 at its bases in Britain.

6. The individual contributions of the other fuel saving items investigated do not appear to be significant. However, collectively they can sum to significant amounts. These items include reduced engine use and taxi time, reduced power take-off, reduced accessory load on engines, delayed flap approach and partial engine taxi. It is suggested that these procedures be implemented whenever possible.

7. A reduction in fuel allocations would impair the user command's capability to meet operational commitments, and in the area of training it would impact the command's state of readiness. This impact could be partially offset by conducting more training during operational missions and by the increased use of simulators for training.

8. During the field trips, discussions with maintenance and operations personnel have indicated that there may be some problems with pressurization losses, which ultimately result in increased fuel consumption. Further investigation in this area may be worthwhile.

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